

THE HALO OCCUPATION DISTRIBUTION OF X-RAY-BRIGHT ACTIVE GALACTIC NUCLEI: A COMPARISON WITH LUMINOUS QUASARS

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ABSTRACT

We perform halo occupation distribution (HOD) modeling of the projected two-point correlation function (2PCF) of high-redshift ($z \sim 1.2$) X-ray-bright active galactic nuclei (AGN) in the XMM-COSMOS field measured by Allevato et al. The HOD parameterization is based on low-luminosity AGN in cosmological simulations. At the median redshift of $z \sim 1.2$, we derive a median mass of $1.02^{+0.21}_{-0.23} \times 10^{13} h^{-1} M_{\odot}$ for halos hosting central AGN and an upper limit of $\sim 10\%$ on the AGN satellite fraction. Our modeling results indicate (at the 2.5σ level) that X-ray AGN reside in more massive halos compared to more bolometrically luminous, optically-selected quasars at similar redshift. The modeling also yields constraints on the duty cycle of the X-ray AGN, and we find that at $z \sim 1.2$ the average duration of the X-ray AGN phase is two orders of magnitude longer than that of the quasar phase. Our inferred mean occupation function of X-ray AGN is similar to recent empirical measurements with a group catalog and suggests that AGN halo occupancy increases with increasing halo mass. We project the XMM-COSMOS 2PCF measurements to forecast the required survey parameters needed in future AGN clustering studies to enable higher precision HOD constraints and determinations of key physical parameters like the satellite fraction and duty cycle. We find that $N^2/A \sim 5 \times 10^6 \text{ deg}^{-2}$ (with N the number of AGN in a survey area of $A \text{ deg}^2$) is sufficient to constrain the HOD parameters at the 10% level, which is easily achievable by upcoming and proposed X-ray surveys.

Subject headings: dark matter, galaxies: nuclei, large-scale structure of the universe, AGN: general

1. INTRODUCTION

Galaxies are believed to reside in dark matter halos and as such make excellent probes of structure formation in the universe (e.g., White & Frenk 1991; Kauffmann et al. 1993; Navarro et al. 1995; Mo & White 1996; Kauffmann et al. 1999; Springel et al. 2005). Observations suggest that there exists a supermassive black hole at the center of every massive galaxy (e.g., Soltan 1982), and hence a physical connection between black holes and their host dark matter halos is naturally expected. The black hole-halo relationship has been widely studied in both semi-analytic models and cosmological hydrodynamic simulations (e.g., Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Marconi et al. 2004; Cattaneo et al. 2006; Croton et al. 2006; Hopkins et al. 2006b; Lapi et al. 2006; Shankar et al. 2004; Di Matteo et al. 2008; Booth & Schaye 2009; Volonteri et al. 2011; Conroy & White 2012). The spatial clustering of black holes can be used to probe this relationship and to obtain constraints on the formation and evolution of supermassive black holes and their role in galaxy formation.

Clustering analyses of different types of active galactic nuclei (AGN) have been widely studied in the literature (e.g., Croom et al. 2004; Porciani et al. 2004;

Croom et al. 2005; Gilli et al. 2005; Myers et al. 2006, 2007a,b; Coil et al. 2007; Shen et al. 2007; Wake et al. 2008; Shen et al. 2009; Ross et al. 2009; Coil et al. 2009; Hickox et al. 2009, 2011; Allevato et al. 2011; Donoso et al. 2010; Krumpel et al. 2010; Cappelluti et al. 2012; White et al. 2012; Shen et al. 2012). Many of these studies employ samples of optically-bright quasars, which provide large sample sizes and accurate redshifts that enable precise measurements of the relationship between the growth of black holes and their parent dark matter halos over a wide range in redshift. However, while quasar clustering has provided a wealth of information on the cosmological evolution of black holes, samples of optical quasars preferentially probe massive black holes accreting at high Eddington rates (Hopkins et al. 2009; Kelly et al. 2010). To fully understand the growth of black holes over cosmic history, we require a systematic study of the relationship between black holes and their host halos spanning a larger range of redshifts, luminosities, and black hole masses. This can be achieved through X-ray surveys.

AGN clustering is most often studied using the two-point correlation function (2PCF; e.g., Arp 1970). For a given cosmological model, the amplitude of the large-scale AGN 2PCF relative to the dark matter 2PCF (i.e., the square of the AGN bias) can be estimated. From the value of this bias factor an estimate of the typical mass of AGN-hosting dark matter halos can then be obtained

(e.g., Jing 1998; Sheth et al. 2001). Previous studies suggest that, compared to optical quasars, X-ray-selected AGN are more strongly clustered and reside in more massive host halos (e.g., Gilli et al. 2005; Coil et al. 2009; Hickox et al. 2009; Allevato et al. 2011; Cappelluti et al. 2012). However, the host halo mass range is insufficiently constrained for a definitive conclusion (for a recent review, see Cappelluti et al. 2012).

Beyond simple bias measurements, a powerful analytic technique known as the halo occupation distribution (HOD) formalism (e.g., Ma & Fry 2000; Seljak 2000; Berlind & Weinberg 2002; Zheng et al. 2005; Zheng & Weinberg 2007) can be used to investigate the full relationship between AGN and their host halos. The HOD is characterized by the probability $P(N|M)$ that a halo of mass M contains N AGN of a given type, together with the spatial and velocity distributions of AGN inside individual halos. As long as the HOD, at a fixed halo mass, is statistically independent of the large scale environments of halos (e.g., Bond et al. 1991), it provides a complete description of the relation between AGN and halos, allowing the calculation of any clustering statistic (e.g., N-point correlation function, void probability distribution, pairwise velocity distribution) at all scales for a given cosmological model. This implies that if the HOD can be constrained empirically, it will encode all of the information that measured clustering properties can convey about AGN formation and evolution.

The HOD approach has been used by several authors to interpret AGN and quasar clustering measurements (e.g., Wake et al. 2008; Shen et al. 2010; Miyaji et al. 2011; Starikova et al. 2011; Allevato et al. 2011; Richardson et al. 2012; Kayo & Oguri 2012). In particular Richardson et al. (2012), and Kayo & Oguri (2012) made clustering measurements of optically luminous quasars for both small (< 1 Mpc) and large scales and performed HOD modeling of the 2PCF to infer the relation between quasars and their host dark matter halos at $z \sim 1.4$. Similar analysis was carried out by Shen et al. (2012) for the quasar-galaxy cross-correlation function (CCF). A natural extension of work on the HOD of optically luminous quasars is to study the black hole-halo relationship for lower luminosity AGN, selected from optical or X-ray surveys. In the current work, we use the 2PCF measurements of Allevato et al. (2011) and a theoretically motivated model of the AGN HOD similar to that used by Richardson et al. (2012) to interpret the spatial clustering of X-ray-selected AGN at $z \sim 1.2$. We compare our results with previous studies of the quasar HOD by Richardson et al. (2012) and construct an evolutionary picture of AGN growth and the role of AGN in large-scale structure formation (similarly to Hickox et al. 2009, but now from the HOD perspective, and at a higher redshift of $z \sim 1$).

Our paper is organized as follows. In §2, we briefly describe our data sets, the parameterization of the AGN HOD, and the theoretical modeling of the 2PCF. We present the results of our HOD modeling in §3. Finally, we discuss the implications of our results in §4 and summarize them in §5. Throughout the paper we assume a spatially flat, Λ CDM cosmology: $\Omega_m = 0.26$, $\Omega_\Lambda = 0.74$, $\Omega_b = 0.0435$, $n_s = 0.96$, $\sigma_8 = 0.78$, and $h = 0.71$. We quote all distances in comoving h^{-1} Mpc and masses in units of $h^{-1} M_\odot$ unless otherwise stated.

2. DATASETS AND METHODOLOGY

In this section we briefly describe our clustering data set and methodology for the HOD analysis.

2.1. Clustering Data Set

We model the projected 2PCF measurements of Allevato et al. (2011) for AGN in the *XMM*-COSMOS survey. COSMOS covers 1.4×1.4 deg² equatorial field¹ and uses multiwavelength data from X-ray to radio bands. *XMM*-Newton surveyed 2.13 deg² of the COSMOS field in the 0.5-10 keV energy band for a total of 1.55 Ms. The resulting *XMM* point source catalog contains 1822 objects, 1465 of which are *XMM*-COSMOS AGN detected in the soft X-ray band (Hasinger et al. 2007; Cappelluti et al. 2007, 2009).

Using the 780 *XMM*-COSMOS AGN that have spectroscopic confirmations, Allevato et al. (2011) applied a magnitude cut of $I_{AB} < 23$ to obtain a clustering sample of 593 X-ray-selected AGN. The sample spans the redshift range 0.0–4.0 with a median redshift of 1.2. The X-ray luminosities of the AGN span the range $\sim 10^{41}$ – 10^{45} erg s^{−1} with a median luminosity of $\sim 6 \times 10^{43}$ erg s^{−1}. We refer the reader to Allevato et al. (2011) for a detailed discussion of the 2PCF calculation.

Correcting for spectroscopic completeness, we find the redshift-averaged observational number density of the AGN to be $(6.7 \pm 0.7) \times 10^{-5} h^3 \text{ Mpc}^{-3}$, where the $\sim 10\%$ uncertainty corresponds to the characteristic level of scatter we observe between the redshift averages computed by discrete summation and by fitting a decaying exponential to the observed redshift distribution (see Figure 1 of Allevato et al. 2011 for the redshift distribution). The 2.13 deg² survey area probes a total volume of 0.09 Gpc³. For this work, we compute the source density by averaging over the volume-weighted number density for each redshift bin (i.e., the number of sources within the redshift range divided by the volume of the redshift slice).

2.2. HOD Modeling

We adopt the theoretical HOD model for AGN proposed by Chatterjee et al. (2012), which was inferred for lower luminosity AGN ($L_{\text{bol}} \leq 10^{42}$ erg s^{−1}) in cosmological simulations. However, Richardson et al. (2012) have found this model to also provide an excellent interpretation of the clustering of quasars observed in the Sloan Digital Sky Survey (SDSS). We therefore apply this particular model to moderate-luminosity X-ray AGN assuming a universality in the general HOD properties of AGN.

This model represents the AGN mean occupation function as the sum of its physically illustrative central and satellite components, $\langle N_{\text{cen}}(M) \rangle$ and $\langle N_{\text{sat}}(M) \rangle$, respectively. The mean occupation function is given as the sum of a softened step function (central component) and a rolling-off power law (satellite component),

$$\begin{aligned} \langle N(M) \rangle = & \frac{1}{2} \left[1 + \text{erf} \left(\frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right] \\ & + \left(\frac{M}{M_1} \right)^\alpha \exp \left(-\frac{M_{\text{cut}}}{M} \right), \end{aligned} \quad (1)$$

¹ centered at J2000 (RA, Dec) = (150.1083°, 2.210°)

where M_{\min} , $\sigma_{\log M}$, M_1 , α and M_{cut} are free parameters. In order to minimize the parameter degeneracy in our modeling, we fix M_{cut} to a value $\ll 10^{12} h^{-1} M_{\odot}$ so that the exponential factor, $\exp(-M_{\text{cut}}/M)$, approaches unity over the range of physical halo masses. This reduces our satellite parameterization to a two-parameter power law.

Using the routine developed in Zheng et al. (2007), we perform a Markov Chain Monte Carlo (MCMC) modeling of the projected 2PCF to sample the four-dimensional parameter space of the AGN HOD. Each MCMC chain discussed herein contains 60,000 points in the HOD parameter space. Since the clustering sample is sparse, we calculate the χ^2 value of each point using only the diagonal elements of the covariance matrix (see, e.g., the appendixes of Myers et al. 2007a; Ross et al. 2009). We fit both the observed 2PCF and number density of AGN to constrain the HOD. This routine includes the effects of halo exclusion, nonlinear clustering and scale-dependent halo bias, where halos are defined as objects with a mean density of 200 times that of the background universe. The halo mass function is computed according to the formula in Jenkins et al. (2001) and the large-scale halo bias factor is computed using the formula in Tinker et al. (2005). We adopt flat priors in logarithmic space for M_{\min} and M_1 and in linear space for α and $\sigma_{\log M}$ ($\sigma_{\log M} > 0$). For improved computational efficiency, we further require that $0.5 < \alpha < 4.0$.

As in Richardson et al. (2012), we adopt the following conventions in our modeling. We assume that the halo occupations of central and satellite AGN are independent (i.e., the number of satellites in a given halo does not depend on whether there is a central AGN), as Chatterjee et al. (2012) found no evidence of a correlation between the activity of central and satellite black holes in a hydrodynamic simulation. For halos of a given mass, we assume that the central occupation numbers obey a nearest integer distribution (Berlind & Weinberg 2002) and the satellite occupation numbers obey a Poisson distribution. This has also been found to be the case for AGN in cosmological simulations (Degraf et al. 2011; Chatterjee et al. 2012). We represent the spatial distribution of satellite AGN within halos as an NFW profile (Navarro et al. 1997) with the concentration-mass relation from Bullock et al. (2001),

$$c(M, z) = \frac{c_0}{1+z} \left(\frac{M}{M_*} \right)^\beta, \quad (2)$$

where M_* is the nonlinear mass for collapse at $z = 0$, and $\beta = -0.13$. We adopt $c_0 = 32$, motivated by the high concentration observed for local AGN (e.g., Lin & Mohr 2007). We have verified that our modeling only weakly depends on c_0 for a wide range of values, from ~ 10 to ~ 60 (Richardson et al. 2012).

To enhance its statistical power, the clustering sample has been constructed over a broad redshift and luminosity range to maximize the volume and the number of sources. The 2PCF obtained in this way can be interpreted as an average over the redshift and luminosity intervals. However, extending this interpretation to the HOD could be problematic since the modeling uses halo properties (e.g., mass function, bias factor) at the median redshift. Redshift evolution of the halo properties

can lead to systematic effects that exceed the statistical uncertainties reflected in the modeling results.

Although a full interpretation of the measured 2PCF would require additional parameters accounting for evolution, Richardson et al. (2012) have demonstrated that the HOD can be meaningfully interpreted as representing the HOD for objects at the median redshift of the sample (to within the quoted uncertainties), if the 2PCF measured over a wider redshift range around the median redshift (i.e., the average 2PCF) is statistically consistent with the true 2PCF of objects at the median redshift. Since we are not in a position to explicitly check this condition for the Allevato et al. (2011) clustering sample, we adopt the median-redshift interpretation with the assumption that the clustering evolves weakly with redshift. See §4.1 and Richardson et al. (2012) for additional discussion regarding this chosen interpretation.

3. RESULTS

We first present the constraints on the AGN HOD obtainable with current data. Then we forecast improvements in the precision of the 2PCF to estimate the requisite observational parameters to obtain high-precision (few percent-level) HOD constraints.

3.1. Current Constraints

In Figure 1 we show our four-parameter HOD fit for X-ray AGN at $z \sim 1.2$. Panel (a) shows the projected 2PCF measurements of Allevato et al. (2011) against the theoretical prediction of our best-fit HOD model (dotted line). We identify the best-fit model as the point in our four-dimensional parameter space associated with the global χ^2 minimum. If we rank all of the models by their χ^2 statistic in ascending order, the first 68% of the models give the range of predicted w_p indicated by the shaded envelope. Our HOD model reproduces the clustering with a reduced χ^2 statistic of 0.34 (total $\chi^2 = 2.39$). Given a χ^2 distribution for seven degrees of freedom, the probability of randomly drawing a χ^2 value less than or equal to 2.39 is only 0.065. This indicates that while the model successfully reproduces the data, the uncertainties quoted on the 2PCF are likely conservative. We discuss this issue further in §4.1.

Panel (b) shows the mean occupation function from the best-fit HOD model, decomposed into its central (dashed line) and satellite (dot-dashed line) components. Similarly to panel (a), the shaded regions indicate the range of the mean occupation function given by the 68% of models with the smallest χ^2 statistic. The panel shows that while reasonable constraints can already be obtained on the central occupation with current data, only an upper limit can presently be obtained on the satellite occupation. This upper limit suggests that, at low redshift, typically only the most massive halos ($> 10^{14} h^{-1} M_{\odot}$) host multiple AGN. It also yields an upper limit on the satellite fraction of X-ray AGN to be $\lesssim 0.1$, where the satellite fraction is defined as the ratio of the number density of satellite AGN (integrated over all halo masses) to the total number density of all AGN. However, we note that this interpretation is sensitive to our choice of satellite parameterization. Alternative models of the mean occupation function (e.g., Kayo & Oguri 2012) allow multiple AGN to reside in low-mass halos.

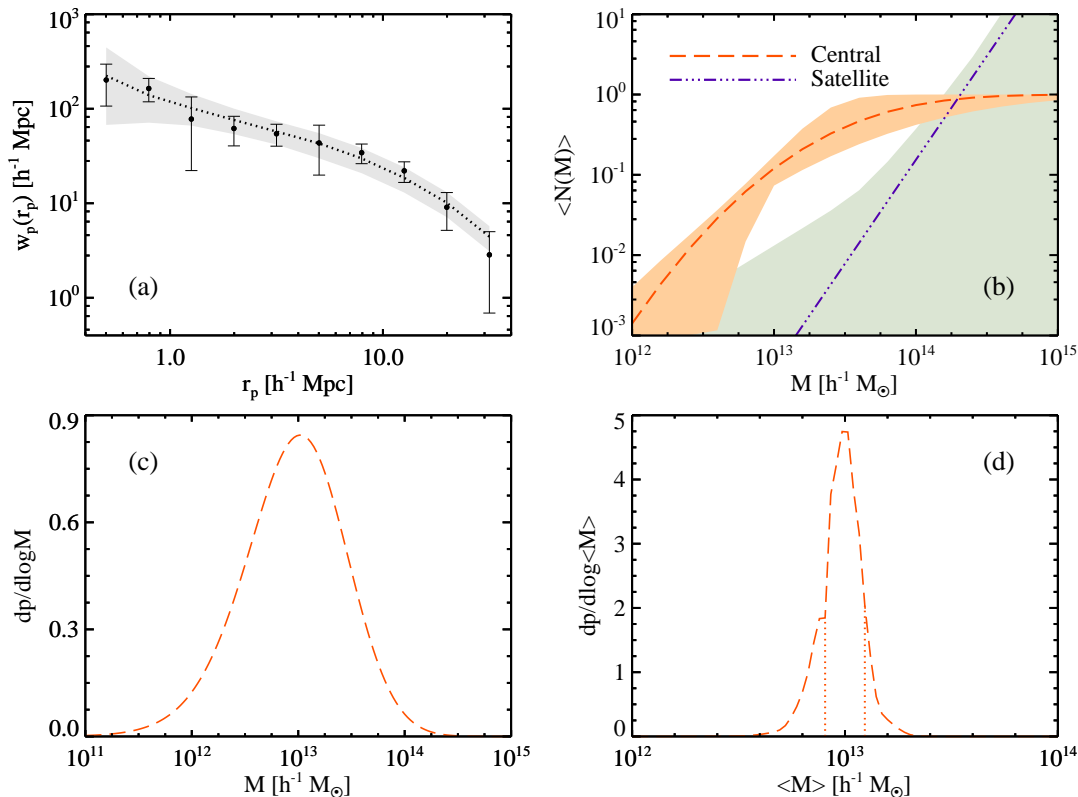


FIG. 1.— HOD fit to the 2PCF of $z \sim 1.2$ X-ray AGN. Panel (a): the projected 2PCF of Allevato et al. (2011; data points and error bars) against the prediction of our best-fit HOD model (dotted line). Panel (b): the mean occupation function of AGN, decomposed into its central (dashed line) and satellite (dot-dashed line) components. In both panels (a) and (b), the shaded envelopes indicate the 68% confidence regions. Panel (c): the full probability density function of host halo masses for central AGN. This distribution is obtained by multiplying the central mean occupation function with the differential halo mass function and averaging over all the models in the MCMC chain (see §3.1 for discussion). Panel (d): the probability density function of the median mass of halos hosting central AGN. This distribution is obtained from the median host halo mass of each model in the MCMC chain. The vertical lines denote the central 68% confidence interval.

Panel (c) shows the full host halo mass distribution (averaged over all points in the MCMC chain) for central AGN. For each model in the MCMC chain, the distribution is derived by multiplying the mean occupation function of central AGN, $\langle N_{\text{cen}}(M) \rangle$, with the differential halo mass function. For a randomly chosen central AGN, the curve is the probability density function for the mass of its host halo. Finally, panel (d) shows the probability density function for the median mass of halos hosting central AGN. At the 68% confidence level, denoted by the dotted vertical lines, we find the median host halo mass for central AGN to be $1.02^{+0.21}_{-0.23} \times 10^{13} h^{-1} M_{\odot}$. We do not depict the corresponding distributions for satellite AGN in this figure—the satellite mean occupation is insufficiently constrained for its halo mass distribution to be robustly determined. We will discuss these HOD constraints further in §4.2.

The central mean occupation function shown in panel (b) of Figure 1 can also be interpreted as the halo mass-dependent duty cycle of AGN (i.e., the fraction of halos hosting a central AGN). We estimate the duty cycle f_o of central AGN around the median host halo mass. For each model in the MCMC chain, we average the predicted

$\langle N_{\text{cen}}(M) \rangle$ over the mass interval spanned by the central 68% of the median host halo mass distribution (shown in panel d of Figure 1). From the normalized distribution of these mass-averages we infer, at the 68% confidence level, an average duty cycle of $f_o = 0.12 \pm 0.02$ for $z \sim 1.2$ X-ray AGN.

3.2. Error Forecasting

Although the physical constraints obtained in §3.1 are consistent with existing estimates, the current precision of 2PCF measurements does not strongly constrain the full range of possible HOD models.

In order to forecast the improvement in HOD modeling precision that can be achieved with planned X-ray surveys, we construct and model a set of simulated 2PCF measurements based on the original measurements of Allevato et al. (2011), but with appropriate rescaling of the error bars. Since the observational AGN number density varies widely between different proposed surveys, an appropriate δw_p scaling relation must account for both survey coverage and depth. As will be discussed in §3.3, for example, a shallow, large-area survey can have a surface density (and thus volume density) an order of

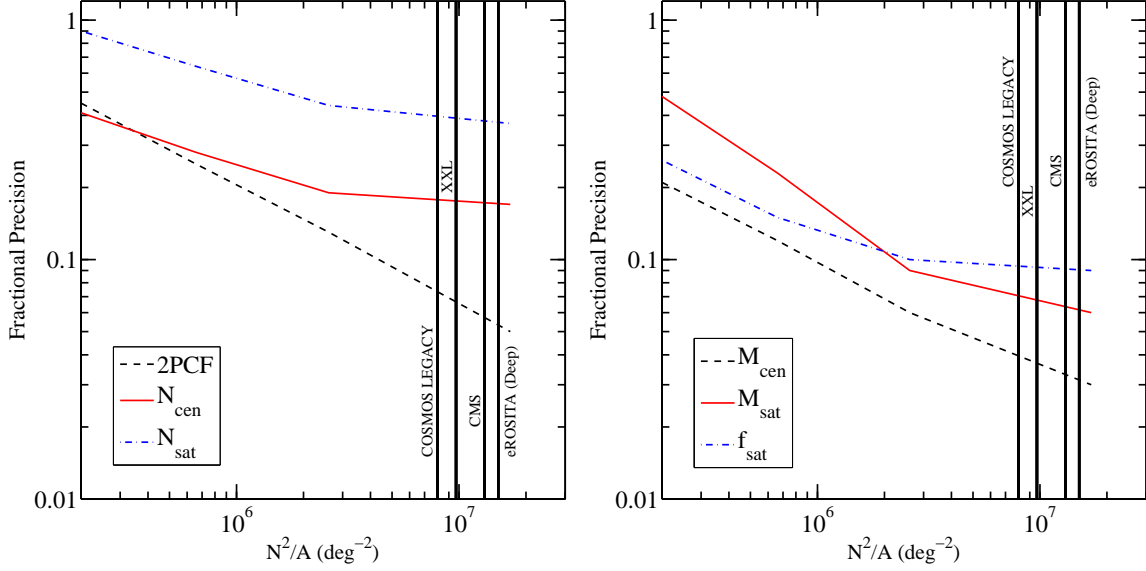


FIG. 2.— The forecasted HOD modeling precision obtainable as a function of the survey N^2/A ratio, where N is the number of sources observed in the survey and A is the survey area. The left panel shows the average fractional uncertainties (see the definition in the text) on the 2PCF (dashed line), central mean occupation function (solid line), and satellite mean occupation function (dot-dashed line). The right panel shows the fractional uncertainties on physical parameters derived from the mean occupation function: the median host halo mass for central (dashed line) and satellite (solid line) AGN and the AGN satellite fraction (dot-dashed line). In both panels, the vertical lines denote the N^2/A value of a particular proposed X-ray AGN survey, as labeled (see Table 1). The “XLL” and “CMS” abbreviations refer to the *XMM*-XLL and *Chandra* 10 deg² surveys, respectively. Our error forecasting indicates that a large improvement in HOD modeling precision can be realized by planned AGN surveys of modest size. See §3.2 and §3.3 for additional discussions regarding the feasibility of different planned surveys.

magnitude smaller than those of deeper surveys. This will significantly impact the observed number of AGN pairs, which determines the overall precision of the 2PCF measurements ($\delta w_p \propto 1/\sqrt{N_{\text{pairs}}}$, with N_{pairs} the number of pairs). If we assume the redshift distribution to be similar for every proposed survey, the number (volume) density of a given survey scales approximately as the number of sources per unit area. Assuming populations with the same clustering, the number of AGN pairs would then scale as the product of the total number of AGN in the survey, N , and the observed AGN surface density, N/A , where A is the angular sky coverage.

We thus rescale our 2PCF error bars according to $1/\sqrt{N^2/A}$ to forecast future HOD constraints. For each r_p bin, we take the corresponding w_p value to be the value of the best-fit 2PCF shown in panel (a) of Figure 1 (i.e., the predicted 2PCF of the HOD model best fitting the Allevato et al. 2011 data). We use the best-fit 2PCF values instead of the original measurements to obtain a “smoothed” data set free of outliers, since artificially reducing the error bar on an outlying data point can potentially cause the HOD modeling to fail. We find that the pair separation range probed by the Allevato et al. (2011) sample, $0.5 h^{-1} \text{ Mpc} < r_p < 30 h^{-1} \text{ Mpc}$, is insufficient to tightly constrain the satellite occupation, irrespective of the measurement precision. While the central occupation is determined by the two-halo term, whose contribution dominates the 2PCF above $\sim 1 h^{-1} \text{ Mpc}$, the satellite occupation is determined by the one-halo term, which dominates at smaller scales. The results of Richardson et al. (2012) suggest that 2PCF measure-

ments to at least $\sim 0.01 h^{-1} \text{ Mpc}$ scales are required to fully constrain the satellite occupation, and we note that larger samples will produce more small-scale pairs, allowing measurement of the 2PCF to smaller scales than was possible with the Allevato et al. (2011) sample.

Hence, in order to isolate the uncertainty in the satellite occupation due to measurement precision, we extend our dummy 2PCF to smaller scales by adding radial bins centered on 0.1, 0.05, and $0.01 h^{-1} \text{ Mpc}$. As with the larger radial bins, we assign to each new bin the w_p value predicted by the HOD model best fitting the Allevato et al. (2011) data. For a small-scale bin centered on r_p with upper and lower boundaries at r_{p2} and r_{p1} , respectively, the uncertainty scales approximately as

$$\delta w_p \propto w_p / \sqrt{\pi(r_{p2}^2 - r_{p1}^2)(2\pi_{\text{max}} + w_p)}, \quad (3)$$

where π_{max} is the maximum line-of-sight separation between AGN pairs. The constant of proportionality can be determined by matching this relation to the existing Allevato et al. (2011) measurements at $r_p < 1 h^{-1} \text{ Mpc}$.

We now define a statistic to describe the overall precision of a given data set in a single number, to which we will refer as the “average fractional uncertainty.” Applied to the projected 2PCF measurements, the average fractional uncertainty is calculated by computing the fractional error on each data point, $\delta w_p(r_p)/w_p(r_p)$, and then averaging the fractional errors over all r_p bins. This statistic is calculated similarly for the central and satellite mean occupation functions, $\langle N_{\text{cen}}(M) \rangle$ and $\langle N_{\text{sat}}(M) \rangle$, respectively, but the halo mass range is restricted to the interval over which the mean occupation

function is greater than 10^{-2} . We impose this condition so as to consider the uncertainty only over the physical halo mass range (i.e., the range that contributes significantly to the AGN number density).

Figure 2 shows the forecasted HOD modeling precision obtainable as a function of the survey N^2/A ratio. The left panel shows the average fractional uncertainties on the 2PCF (dashed line), central mean occupation function (solid line), and satellite mean occupation function (dot-dashed line). The right panel shows the fractional uncertainties on physical parameters derived from the mean occupation function: the median host halo mass for central (dashed line) and satellite (solid line) AGN and the AGN satellite fraction (dot-dashed line). In both panels, the vertical lines denote the N^2/A value of a particular proposed X-ray AGN survey, as labeled. Our error forecasting indicates that a large improvement in HOD modeling precision can be realized by planned AGN surveys of modest size. For a survey of area equal to that of the *XMM*-COSMOS field (2.13 deg^2), for example, we find that a sample of $\sim 1,000$ AGN with spectroscopic redshifts will be sufficient to double the precision of current constraints, and a sample size larger than 10,000 will allow determination of the derived physical parameters to better than 10% statistical uncertainty. In the next section we discuss the plausibility of current and future X-ray surveys in achieving this precision.

3.3. Survey Design

Based on our error forecasts we now evaluate our predictions in light of ongoing and future surveys of X-ray AGN. In Table 1 we show the relevant source statistics. The number counts are obtained using the predictions of the cosmic X-ray background model of Gilli et al. (2007)² and sensitivity curves for various X-ray surveys. All X-ray luminosities and fluxes are quoted in the 0.5-2 keV band. The counts are for sources detected at all redshifts (the redshift distribution peaks at $z \sim 1$ independent of flux limit). The parameters f_{20} and f_{80} represent the flux limits at 20% and 80% of the total survey area, respectively. These two numbers are useful in providing a more accurate shape of the sensitivity curve. In column 8 of Table 1 we compute the approximate source densities (number of yield per unit area) of relevant X-ray surveys. It is important to note that the larger area, shallower surveys have smaller surface densities (and thus volume densities) than the deeper surveys. This potentially affects the number of pair counts in clustering studies.

We find that the *Chandra* COSMOS Legacy Survey, the *XMM*-XXL Survey, and a *Chandra* medium-area ($\sim 10 \text{ deg}^2$) survey can all obtain high-precision HOD constraints. However, as mentioned previously, our requirement that spectroscopic redshifts be obtained for our sources may prove challenging for a 50 deg^2 survey like *XMM*-XXL. Hence we emphasize that a deeper survey covering a smaller area is preferable for HOD studies, given that the surface density of sources is larger in this case and follow-up spectroscopy is better facilitated³. It is evident from Table 1 that either the COSMOS Legacy Survey or a medium-area *Chandra* survey can be utilized to study luminosity evolution

of the HOD. The Allevato et al. (2011) clustering sample has been constructed over a wide luminosity range ($10^{41} - 10^{45} \text{ erg s}^{-1}$) and our HOD precision estimates in Figure 2 are obtained using the median-redshift/median-luminosity interpretation. While these precision forecasts are robust in terms of statistical uncertainties, with increasing statistical precision in the 2PCF, systematic effects from luminosity and/or redshift evolution will become increasingly important and may limit the ultimate precision of constraints obtainable on the HOD (i.e., the median-redshift/median-luminosity interpretation may no longer apply; see §4.1). In this case, more sophisticated HOD models with parameters accounting for redshift and/or luminosity evolution would be warranted.

In both panels of Figure 2, all of the fractional precision curves for the HOD modeling scale (roughly) linearly with the precision curve for the 2PCF before flattening once it surpasses $\sim 10\%$ precision (near $N^2/A \sim 2 \times 10^6 \text{ deg}^2$). The characteristic shape of these curves arises from a transition in the dominant source of statistical uncertainty in the modeling. As the fractional uncertainty of the 2PCF decreases with increasing N^2/A , it eventually falls below the fractional uncertainty of the AGN number density, which we have fixed to 10%. We investigated a wide range of number densities and fractional uncertainties (up to a factor of ~ 5 variation) to determine their impact on our HOD modeling results. In all cases, we recovered similar curves to those shown in Figure 2 which flattened near the N^2/A value of 2PCF-number density fractional uncertainty equality. Since the planned surveys discussed herein all fall within the number density-limited regime ($N^2/A > 2 \times 10^6 \text{ deg}^2$), we note that their forecasted precisions are limited by the assumed 10% uncertainty in the number density, rather than the precision of the 2PCF, and therefore may be conservative estimates. If the systematics of the surveys can be controlled to better than 10% (which we do not assume), it may be possible to obtain slightly tighter constraints on the HOD than those indicated here.

Finally, we note that the survey error forecasts presented herein are calculated for AGN *auto*-correlation measurements. Although it is beyond the scope of the current work, some studies have suggested that even higher precision clustering constraints may be achievable through the cross-correlation between AGN and galaxies (see Hickox et al. 2009 and Coil et al. 2009 for examples using X-ray AGN) and could possibly lead to HOD constraints if the galaxy population is well-characterized (see, e.g., Wake et al. 2008; Shen et al. 2012).

4. DISCUSSION

We now discuss the systematic issues and theoretical aspects of our analysis.

4.1. Systematic Uncertainties

As mentioned previously, we apply the median-redshift/median-luminosity interpretation of

² <http://www.bo.astro.it/~gilli/counts.html>

³ Novel statistical techniques have been developed to maximize the precision of clustering measurements using photometric redshift samples (Myers et al. 2009; Hickox et al. 2011), but the statistical power of these measurements is necessarily limited compared to spectroscopic studies using comparable sample sizes.

TABLE 1
AGN SOURCE COUNTS IN X-RAY SURVEYS

Survey	Area (A) (deg ²)	f_{20} (erg cm ⁻² s ⁻¹)	f_{80} (erg cm ⁻² s ⁻¹)	Number(N)/log[L_X /(erg s ⁻¹)] bin			N/A (deg ⁻¹)	N^2/A (deg ⁻²)	Ref
				42–43	43–44	44–45			
<i>Chandra</i> COSMOS Legacy	2	2.0×10^{-16}	3.7×10^{-16}	1600	2100	460	2000	8×10^6	(1)
<i>Chandra</i> 10 deg ² survey	9	6.1×10^{-16}	7.9×10^{-16}	2900	6300	1900	1200	1.3×10^7	(2)
<i>XMM</i> –XXL	50	3.1×10^{-15}	1.0×10^{-14}	1300	5800	4000	440	9.7×10^6	(3)
eROSITA (Deep)	100	3.1×10^{-15}	3.2×10^{-15}	4700	21000	12000	380	1.5×10^7	(4)
eROSITA (All Sky)	41253	10^{16}	10^{-16}	320000	1600000	2000000	95	3.7×10^8	(5)

NOTE. — The values in columns N/A and N^2/A are calculated over all luminosity bins ($42 < \log[L_X/(\text{erg s}^{-1})] < 45$). References: 1. F. Civano (private comm.), 2. Scaled from Kenter et al. (2005), 3. Elyiv et al. (2012), Pierre (2012) 4. Merloni et al. (2012), 5. Merloni et al. (2012).

Richardson et al. (2012) to our HOD modeling. Within this interpretation, the HOD can be taken to represent AGN at the median sample redshift if the luminosity and redshift evolution of the 2PCF are weak (i.e., their systematic effects do not exceed the statistical uncertainty quoted on the modeling results). Richardson et al. (2012) provide a detailed discussion of how intrinsic luminosity or redshift evolution of the clustering would affect the HOD modeling.

To high precision, the clustering of optically-selected quasars has not been found to exhibit significant luminosity evolution (e.g., Croom et al. 2005; Myers et al. 2007a; Shen et al. 2009, 2012). Available studies on the luminosity evolution of X-ray AGN clustering do not show any evidence for strong evolution at $z \sim 1$ (e.g., Coil et al. 2009), although Krumpke et al. (2010) demonstrated significant luminosity evolution of clustering at $z \sim 0.25$. Future studies with larger samples of X-ray-selected AGN are needed to confirm the degree of luminosity evolution in X-ray AGN samples. Since the luminosity evolution at $z \sim 1$ has not been well quantified, we assume that the luminosity evolution is weak and is incorporated within the uncertainties of the 2PCF.

There has not been a comprehensive study of the redshift evolution of the clustering of X-ray-selected AGN (due to small sample sizes). However, we examine the redshift evolution of bias from the Allevato et al. (2011) sample to infer the approximate redshift evolution of the 2PCF. Allevato et al. (2011) measure the bias of the full sample (median $\langle z \rangle = 1.2$) to be $b = 2.98 \pm 0.13$. They then construct a sub-sample spanning a smaller redshift interval, but with a similar median redshift ($\langle z \rangle = 1.3$) to that of the full sample, and evaluate the bias of the sub-sample to be $b = 3.10 \pm 0.18$. The consistency between the clustering amplitudes over the whole redshift range and in the narrow redshift range around the median redshift therefore lends supports to our interpretation of the HOD modeling results.

Richardson et al. (2012) provide a thorough discussion on the implications of alternative HOD models on the quasar 2PCF. In short, Richardson et al. (2012) found the central occupation to be robust to the chosen HOD parameterization but found the satellite occupation to exhibit statistically significant model-dependences at high halo masses. This systematic effect led to a statistically significant difference in some physical parameters. For example, the quasar satellite fractions obtained from HOD modeling by Kayo & Oguri (2012) and

Richardson et al. (2012) disagreed with each other by a large factor (two substantially different HOD models were assumed by the two different groups). Although breaking this degeneracy in the high-mass satellite occupation will require larger samples of small-separation pairs coupled with additional constraints (e.g., the distribution of line-of-sight pair velocities), it is not of central concern to the current X-ray AGN constraints presented herein. Our modeling is unable to impose strong constraints on the form of the satellite occupation due to the lack of small-scale clustering data ($< 1 h^{-1}$ Mpc).

As an additional check, we generalize the form of our central HOD parameterization by allowing the softened step function to approach an arbitrary asymptotic value less than unity (see Eq. 1) and repeat the modeling of the Allevato et al. (2011) data. We find that the HOD fit is statistically insensitive to this new degree of freedom, and we recover similar relative uncertainties to those yielded by the original model. Although our chosen model has been calibrated for low-luminosity AGN, we emphasize that the current model has successfully reproduced quasar clustering and has been favored by direct measurements of the mean occupation function of X-ray AGN (Allevato et al. 2012). We compare our HOD constraints obtained from modeling the 2PCF to those directly inferred for X-ray AGN by Allevato et al. (2012) in §4.2.

Finally, while our HOD model successfully reproduces the observed clustering of X-ray AGN, it fits the data with a reduced χ^2 statistic of 0.34. This suggests either that our HOD model admits too many free parameters, thereby overly fitting the details in the 2PCF, or that the error bars quoted on the 2PCF overestimate the true 1σ uncertainty. To test whether the four-parameter model overfits the data, we fit only the central occupation function to the two-halo term (all data points at $r_p > 1 h^{-1}$ Mpc) with the parameter $\sigma_{\log M}$ fixed to the best-fit value yielded by the full modeling. Hence we only fit a single free parameter, M_{\min} , to nine data points. Even with most of the freedom of the HOD model eliminated, the modeling still reproduces the data with a reduced χ^2 statistic of ~ 0.4 . We interpret this to indicate that the bootstrap errors estimated by Allevato et al. (2011) are likely a conservative estimate of the true uncertainty. As a caveat to our modeling, however, we note that neglecting the covariance in the 2PCF measurements can also potentially lead to an overfitting of the data.

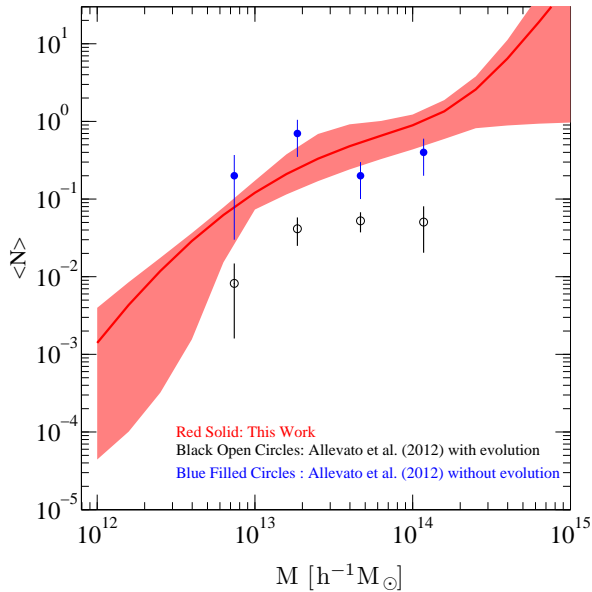


FIG. 3.— Comparison of the total mean occupation function of X-ray AGN as empirically measured with a group catalog by Allevato et al. (2012; blue filled circles) to the 2PCF modeling inference from the current work (red solid line). The red shaded region indicates the 68% confidence interval of our modeling (see the text). The black open circles represent the empirically-measured mean occupation function of Allevato et al. (2012) after correcting for redshift and luminosity evolution of the X-ray AGN. See §4.2 for further discussion on the comparison between the two measurements.

4.2. Comparison with Previous Work

Our analysis suggests that the 68% confidence interval for the best-fit host halo mass of central X-ray AGN is $12.90 \leq \log[M_{\text{cen}}/(h^{-1} M_{\odot})] \leq 13.09$. Using a simple HOD model consisting of only central AGN and characterized by a delta function for the occupation distribution, Allevato et al. (2011) obtained a host halo mass of $\log[M_{\text{cen}}/(h^{-1} M_{\odot})] = 12.97 \pm 0.06$, which is consistent with our result. Previously, Coil et al. (2009) measured the CCF of X-ray AGN selected from the All-Wavelength Extended Groth Strip International Survey with a control sample of galaxies and obtained a minimum host halo mass of $5_{-3}^{+5} \times 10^{12} h^{-1} M_{\odot}$, which is also consistent with our result. The median redshift and luminosity of their AGN sample, 0.90 and $10^{42.8} \text{ erg s}^{-1}$, respectively, are similar those of the Allevato et al. (2011) sample.

A related study was carried out by Starikova et al. (2011). Using a sample of X-ray-selected AGN in the *Chandra* Boötes field ($41 \leq \log[L_X/(\text{erg s}^{-1})] \leq 45$), they performed HOD modeling by comparing the correlation function projected parallel and perpendicular to the line of sight. For $0.17 \leq z \leq 3.0$, their analysis preferred a host halo mass scale $> 4.1 \times 10^{12} h^{-1} M_{\odot}$ and found that AGN reside primarily in central galaxies. The derived host halo mass scale is consistent with our results but our satellite occupation is insufficiently constrained for a quantitative comparison of satellite fractions.

Recently, Allevato et al. (2012) used a novel approach to directly measure the occupation function of X-ray AGN in groups and clusters. In Figure 3 we compare

our total mean occupation function obtained from modeling the 2PCF (solid red line) to the direct measurement of Allevato et al. (2012)⁵ (filled blue circles). The error-bars correspond to the 1σ errors in mass and occupancy and the red shaded region represents the 68% confidence interval of our modeling. The best-fit values of our HOD parameters are as follows: $\log[M_{\text{min}}/(h^{-1} M_{\odot})] = 13.65_{-0.05}^{+0.1}$, $\sigma_{\log M} = 0.78_{-0.06}^{+0.09}$, $\log[M_1/(h^{-1} M_{\odot})] = 14.32_{-2.15}^{+7.87}$, and $\alpha = 2.59_{-1.87}^{+0.33}$. It is evident from Figure 3 that the two complimentary measurements are consistent with each other, thus validating the HOD parameterization that we have used in the 2PCF modeling. As previously mentioned, the model was developed using numerical simulations of lower luminosity AGN and has been applied to the current sample under the assumption of universality in the general AGN HOD properties.

Allevato et al. (2012) attempt to correct their measurement of the mean occupation function for luminosity and redshift evolution. The measurements, represented by the black open circles in Figure 3, appear to disagree with our results at the 1.7σ level. Physically, our $\langle N(M) \rangle$ can be interpreted as the mass-dependent AGN occupation fraction at $z \sim 1.2$, under the assumption of weak luminosity and redshift evolution (see §4.1). We note that the Allevato et al. (2012) sample consists of AGN at $z < 1.0$ and with slightly lower X-ray luminosities than the sample of Allevato et al. (2011), whose 2PCF measurements we model in the current work. While it is possible that this disagreement in the occupation fraction could arise due to luminosity and/or redshift evolution of the X-ray AGN population, we emphasize that it could also arise simply due to an over- or under-correction for evolution. Conclusively identifying the source of this discrepancy will require studies of redshift and luminosity evolution with larger AGN samples.

4.3. Implications for AGN Evolution

From the measured clustering of AGN at different wavelengths and at different redshifts one can draw an evolutionary picture of AGN growth and connect it to the cosmic growth of structure (popularly known as ‘AGN co-evolution’ in the literature). We now interpret our HOD result within this co-evolution paradigm. We adopt the evolutionary picture presented in Hickox et al. (2009), which has been successful in interpreting several theoretical aspects of the co-evolution scenario, to assess our findings. We will focus on the results of Richardson et al. (2012) for the quasar HOD at $z \sim 1.4$ and the results of the current paper for the X-ray AGN HOD at $z \sim 1.2$. Critically, the X-ray AGN we consider are substantially less bolometrically luminous than quasars. The Hickox et al. (2009) picture has been evaluated primarily on the basis of moderate-redshift observations ($z \sim 0.5$). We now extend this picture to a higher redshift ($z \sim 1$).

In this picture, massive galaxies follow an evolutionary sequence from a gas-rich star-forming quasar phase, to a spheroid with lower star formation and AGN ac-

⁶ There is a typographical error in the coefficients of the $L_X - M$ scaling relation in Allevato et al. (2012). The correct coefficients (Leauthaud et al. 2010) have been adopted in determining the masses of the X-ray groups and clusters in the paper (V. Allevato, private comm.).

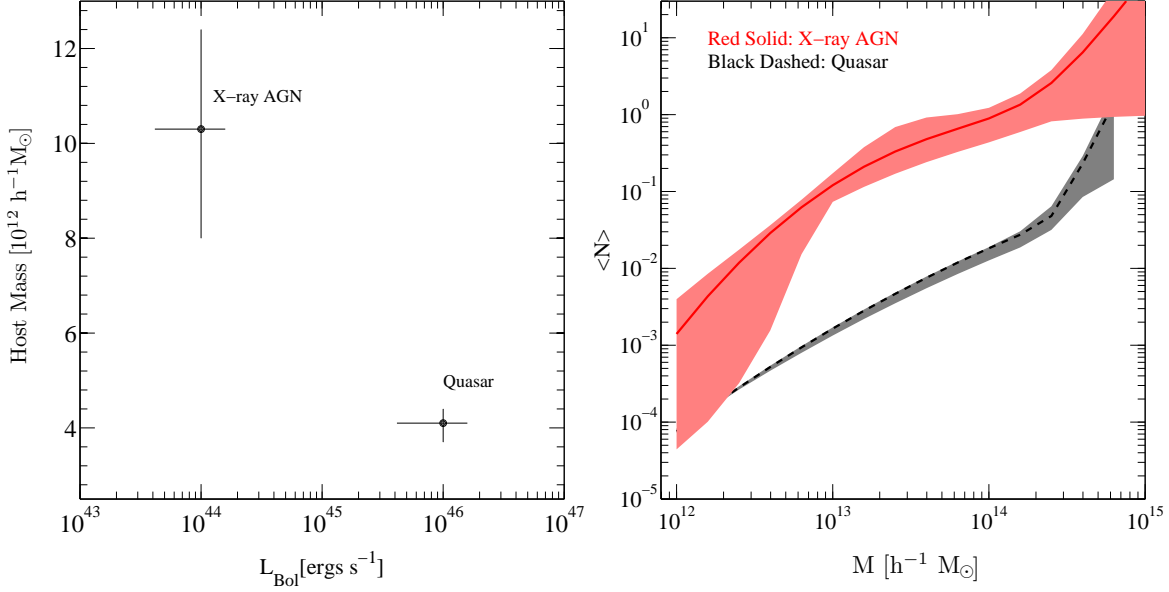


FIG. 4.— Left panel: the median halo mass of quasars and X-ray AGN as a function of bolometric luminosity at $z \sim 1$, as labeled. The quasar result is obtained from Richardson et al. (2012) and the X-ray AGN constraint is from the current work. Both values are obtained from HOD modeling of the 2PCF. This shows that there is a 2.5σ difference between the host halo masses of quasars and X-ray AGN, with the latter residing in higher mass halos. This result is similar to the evolution picture presented in Hickox et al. (2009) for AGN at $z \sim 0.5$, but now performed at significantly higher redshift (see also §4.3). Right panel: the predicted total mean occupation function for quasars (dashed line; Richardson et al. 2012) compared to the predicted total mean occupation function of X-ray AGN (solid line; current work).

tivity, to a red-and-dead galaxy with discrete radio outbursts from the central AGN (e.g., Croton et al. 2006; Hopkins et al. 2008; Hickox et al. 2009). The gas-rich quasar phase could be possibly driven by major mergers (e.g., Kauffmann & Haehnelt 2000; Hopkins et al. 2006a, 2008) or by secular instabilities (e.g., Bower et al. 2006). It is believed to occur at a typical halo mass scale of a few times $10^{12} M_{\odot}$ at almost all redshifts and may result from a natural evolution of the halo-galaxy mass relation, given that galaxy formation is most efficient at those halo mass scales (e.g., Conroy & White 2012) and powerful starbursts galaxies are found in halos of similar mass (see Hickox et al. 2012 and references therein). In this phase the central black hole undergoes Eddington accretion and shines as a luminous quasar.

From the quasar phase galaxies transition into the spheroid phase characterized by lower star formation and declining AGN activity. These spheroids reside in halos of mass $\sim 10^{13} M_{\odot}$. Their central black holes undergo moderate accretion ($0.001 - 0.1$ Eddington) and shine as X-ray-bright AGN. The cause of this decline in AGN activity is not yet known, but a popular model involves a lack of cold gas due to shock heating inside the halo (e.g., Birnboim & Dekel 2003; Kereš et al. 2009) or feedback from the AGN itself (e.g., Silk & Rees 1998; Di Matteo et al. 2005). At even later times, galaxies enter the red-and-dead phase in which the central AGN becomes extremely radiatively inefficient. Continued growth of the host halo completely shock-heats the intra-halo gas. From clustering studies Hickox et al. (2009) demonstrated that X-ray AGN reside in dark matter halos in the mass range of $\sim 10^{13} h^{-1} M_{\odot}$. Using a sample of radio AGN, which have very low accretion efficiencies, Hickox et al. (2009) also demonstrated that

radio AGN are found in halos of mass $\sim 3 \times 10^{13} h^{-1} M_{\odot}$ or greater, consistent with the results of several other studies (e.g., Wake et al. 2008; Mandelbaum et al. 2009; Donoso et al. 2010).

Richardson et al. (2012) found the median host halo mass of central quasars at $z \sim 1.4$ to be $4.1^{+0.3}_{-0.4} \times 10^{12} h^{-1} M_{\odot}$, which is significantly (2.5σ) lower than the corresponding host halo mass scale of X-ray-selected AGN near this redshift. The left panel of Figure 4 shows the respective locations of quasars and X-ray AGN in (bolometric) luminosity-host halo mass space. It is apparent that, at $z \sim 1$, X-ray AGN with low bolometric luminosities reside in halos of significantly higher mass than quasars with bolometric luminosities at least two orders of magnitude higher. Since, even at higher redshifts, higher luminosity AGN (i.e., quasars) reside in halos of lower mass compared to lower luminosity AGN, we confirm that the correlation between AGN luminosity and host dark matter halo mass is relatively weak. Moreover, black holes indeed appear to undergo the quasar phase near the critical mass limit of $\sim 10^{12} M_{\odot}$ and generally become less active as the halo grows in mass. Thus our detailed HOD modeling supports the Hickox et al. (2009) picture at high redshift.

We note that the “cartoon” picture presented in Hickox et al. (2009) is valid only for *central galaxies*. The fact that our HOD modeling shows that AGN reside primarily in central galaxies validates interpreting the AGN population within this picture. An HOD analysis of the 2PCF of high-redshift radio-selected AGN could further constrain this evolutionary picture. Some studies have suggested that, at high redshift, the CCF of radio-loud quasars with their radio-quiet counterparts does show more clustering strength than the auto-correlation func-

tion of radio quiet quasars (e.g., Shen et al. 2009), which would indicate that radio-loud quasars reside in more massive halos.

From the average duty cycle measurements of quasars and X-ray AGN we can infer a characteristic lifetime of these objects. The lifetime can be approximately estimated as $t_o = f_o \times t_H$ (Martini & Weinberg 2001; Croton 2009; Hopkins & Hernquist 2009a), where t_H is the Hubble time and f_o is the average duty cycle. For our purpose, the duty cycle can be estimated as the occupation fraction of AGN or quasars at the median redshift, which is shown in the right panel of Figure 4. For quasars, (Richardson et al. 2012) obtained an average duty cycle of $f_o = 7.3^{+0.6}_{-1.5} \times 10^{-4}$ at $z \sim 1.4$. The Hubble time is roughly 6 Gyr at $z \sim 1$, yielding a characteristic quasar lifetime of ~ 4.4 Myr. Similarly, from the HOD modeling results of the current work, we find a characteristic X-ray AGN lifetime of ~ 0.7 Gyr. Since these lifetimes invoke duty cycles calculated for the median host mass scale, we interpret these timescales as the mean lifetime of a “typical” quasar or AGN at $z \sim 1$.

We can compare our estimates of lifetime with the semi-analytic predictions of Hopkins & Hernquist (2009b). Using an observed distribution of Eddington ratios and AGN model light curves, Hopkins & Hernquist (2009b) found that a black hole spends different amounts of time at different stages of its evolutionary sequence. The lifetime at high Eddington ratios (≥ 0.1) is typically 10 – 100 Myrs and at moderate Eddington ratios (0.001 – 0.1) is typically 0.5 – 1 Gyr. Our current sample of X-ray-selected AGN are likely to have moderate Eddington ratios (e.g., Hickox et al. 2009) while the quasar population is representative of the high accretion stages of a black hole. Our estimated lifetimes, both for the highly accreting quasar phase and the moderately accreting X-ray phase, are in broad agreement with the Hopkins & Hernquist (2009b) prediction. As we do not have a catalog of the masses of our black holes, this comparison is necessarily mostly qualitative in nature. It has been discussed in Hopkins & Hernquist (2009b) that the lifetimes of black holes are a function of several parameters (e.g., black hole mass, luminosity, host halo mass). Hence a more accurate comparison of lifetimes with the Hopkins & Hernquist (2009b) picture is possible with black hole mass measurements of our quasar and X-ray AGN samples. Qualitatively, our results independently support the idea that black holes spend significantly different times in different phases of their evolutionary sequence. On average, we find the lifetime of black holes in the moderate Eddington phase to be ~ 100 times longer than that of the quasar phase. We summarize the key findings of our analysis in the following section.

5. SUMMARY OF RESULTS

We perform an HOD analysis of the projected 2PCF of X-ray-selected AGN at $z \sim 1.2$. We use a physically-motivated HOD model based on low-luminosity AGN in cosmological simulations, but which has also been found to provide an excellent description of the clustering of quasars (Richardson et al. 2012) and the mean occupation empirically measured for X-ray AGN (Allevato et al. 2012). Our modeling yields a median mass for halos

hosting central AGN of $1.02^{+0.21}_{-0.23} \times 10^{13} h^{-1} M_\odot$ and an upper limit on the AGN satellite fraction of ~ 0.10 , which are consistent with previous estimates. Our 2PCF data sample an insufficient range of the one-halo term to conclusively rule out a monotonically decreasing satellite occupation at high halo mass, but we find that our analysis strongly favors a positive slope.

Since Richardson et al. (2012) inferred a host halo mass of $4.1^{+0.3}_{-0.4} \times 10^{12} h^{-1} M_\odot$ for central quasars at similar redshift, we show that X-ray AGN reside in halos of significantly (2.5σ) higher mass compared to quasars at $z \sim 1$. We also show that at $z \sim 1$, the average lifetime of the X-ray AGN phase is ~ 100 times longer than that of the quasar phase. The derived mass scales and lifetime estimates support the Hickox et al. (2009) picture of AGN evolution (established at low redshift), where black holes are believed to follow an evolutionary sequence from a high-Eddington quasar phase to a moderately accreting X-ray phase, to a radiatively inefficient radio phase.

Based on our current analysis, we project the 2PCF measurements of Allevato et al. (2011; with appropriate rescaling of the error bars) to forecast the improvement in HOD modeling precision that can be achieved with future X-ray surveys. For a survey of equal area to *XMM-COSMOS*, we find that a sample of $\sim 3,000$ AGN is sufficient to constrain the HOD at the 20% level, while a sample size greater than 10,000 will enable characterization of the HOD to at least the 10% level (and possibly better, depending on survey systematics). However, realizing this precision for the satellite occupation and its derived parameters will require measuring the 2PCF to smaller pair separation scales. Based on the results of Richardson et al. (2012), we argue that this minimum scale is $\sim 0.01 h^{-1}$ Mpc. This should be possible with future X-ray surveys, whose larger volumes will contain greater number of small-scale pairs. Our projections show that ongoing and proposed X-ray surveys such as the *Chandra* COSMOS Legacy survey, a *Chandra* medium-area survey, and the eROSITA mission will easily obtain $\sim 10\%$ -level precision, provided that there is sufficient optical spectroscopic follow-up to obtain accurate redshifts. Accurately determining the AGN HOD will enable key physical parameters like the AGN satellite fraction and duty cycle to be inferred with unprecedented precision, making possible a definitive evaluation of the AGN co-evolution paradigm.

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